Coolant Mixing in Multirod Fuel Bundles

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COOLANT MIXING IN MULTIROD FUEL BUNDLES

by

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DOR Design Study

Special Report

Connected with a
Study of a Proposed Heat Transfer Experiment
with a Multirod Element

A B S T R A C T

The report gathers together the available experimental data in the literature on mixing rates between sub-channels for axial flow in multi-rod fuel bundle assemblies both with and without mixing promoters. The data are compared to mixing rates predicted by various methods.

The data for mixing around bare rods, without mixing promoters, is somewhat erratic and hard to predict within a factor of 3. Mixing with fins or wire wraps, however, seems more systematic and easier to predict. In the range of data available, predictions seem to be as good as ± 50%.

TABLE OF CONTENTS

List of Symbols

General:

A	Cross section area.
A_f	Cross section area swept by fins.
b	Wetted perimeter.
c	Concentration of chemical species, energy, or momentum.
c_p	Specific heat.
CV	Correlating variable, equation (15).
d	Perimeter of interface in fluid.
D	Diameter of rod.
f	Friction factor, equation (1).
h_i, h_k	Convective heat transfer coefficient, equation (3).
h	Height of fins or wire wraps.
n	Number of fins or wraps on one rod.
p	Pitch of helical fin or wire wrap on a rod.
P	Pressure.
r	Radius coordinate, measured from center of a rod.
R	Ratio of predicted mixing, equation (14) to measured mixing.
Re	Reynolds Number.
S	Rod pitch in the bundle
t	Temperature.
V	Velocity.
w	Mass flow rate.

x	Axial distance (in direction of rod axes).
y	Distance, equations (2) and (4).
δ	Distance between centroids of adjacent sub-channels.
Δ	Denotes difference.
ϵ	Eddy diffusivity, defined by equation (1).
θ	Angle subtended by a sub-channel, measured from the center of an adjacent rod.
μ	Dynamic viscosity.
ν	Kinematic viscosity $\triangleq \mu/\rho$.
π	pi, 3.14 ....
ρ	Density of fluid.
σ	Peripheral distance between adjacent fins on one rod.
$\sum$	Summation sign.
ω	"Rotational velocity" of fins, equation (A-3).

Subscripts:

i, k	Denote sub-channels.
ik	Denotes the interface, in the fluid, between adjacent sub-channels, or the distance between sub-channels, or "between i and k".
j	Index for the various solid surfaces in a given sub-channel.

Other Symbols:

$\approx$	Approximately equal to.
$\triangleq$	Equal to by definition, defined as
'	denotes "per unit length of flow".

INDEX TO THE FIGURES

I. INTRODUCTION:

This report deals with an important special aspect of the prediction of the velocity and temperature distribution in reactor core passages of the rod bundle type. The basic problem involves what is variously called "mixing" or "turbulent interchange" or "eddy diffusion". The purposes of this report are to define and illustrate the problem, to gather together the data on mixing available in the open literature and to reduce the data to common terms, to compare the data, and to seek out some pattern for predicting the size of mixing in a given situation.

The following section illustrates how the problem arises. The illustrations employ the lumped parameter or finite difference approach, considering flow passages which are not arbitrarily small, in contrast to the approach which is required to derive the differential equations of momentum and energy flow in the core-passages. This finite difference approach follows both the methods commonly used in core-passage flow and heat transfer computations, and also the methods employed in most instances to reduce the mixing data collected over the past several years.

Sections III and IV of this report present the data gathered from the literature, and describe predicting methods suitable for clarifying the trends in the data and, to a limited extent, for predicting mixing in a given circumstance. The presentation divides the mixing problems into two general types: mixing in channels of "bare" rods, and mixing around rods with fins, wire wraps, or other mixing promoters.

Section V summarizes the overall conclusions of the report.

II. ILLUSTRATIONS OF MIXING TERMS:

II.A. PRESSURE DROP AND VELOCITY PROFILE CALCULATION - THE MOMENTUM EQUATION:

The finite difference approach divides the total flow passage into a convenient number of smaller sub-passages as shown in Figure 1. To predict the velocity profile and the overall pressure drop requires the momentum equation for each sub-passage. To keep this illustrative discussion simple, we shall assume that the coolant has a constant density and that no objects protrude into the sub-channels, that is, that the sub-channel cross-sections are uniform with length. (The equations can easily be extended. See, for example, reference (1), on which much of this discussion is based).

For the k-th sub-channel the momentum relation determines the velocity:

$$A_k \Delta p_k = f_k \rho \frac{v_k^2}{2} b_k L_k + \sum_i \rho \epsilon_{ik} d_{ik} L_k \frac{(v_k - v_i)}{\delta_{ik}} \quad (1)$$

On the right hand side, the first term represents forces due to friction at the solid boundaries of the sub-channel, while the last term represents forces due to momentum exchange at those sub-channel boundaries (denoted by the subscripts $_{ik}$) which lie in the fluid. This term contains the velocity gradient, which we approximate by the term

$$(v_k - v_i)/\delta_{ik},$$

and the eddy diffusivity ϵ_{ik}, which is, in effect, defined by this equation.

(The equivalent differential form of the momentum exchange term is the familar expression

$$\rho\epsilon \text{ (differential area) } \frac{\partial V}{\partial y} , \qquad (21)$$

where y indicates the direction normal to the differential area.)

The last term of equation (1) is called the "mixing" or "interchange" term because it represents interactions between the fluid flows in adjacent sub-channels. The main body of this report is concerned with estimating the size of this term.

Before we begin that subject, however, it will be helpful to consider another equation in which there is a mixing term: the energy equation.

II.B. COOLANT TEMPERATURE CALCULATIONS - THE ENERGY EQUATION:

The total flow passage is imagined to be divided into a convenient number of sub-channels, as was the case for the momentum equation. This time, however, the conservation of energy equation for the k-th sub-channel pertains:

$$w_k c_p \frac{dt_k}{dx} = \sum_j h_k b_{kj} (t_j - t_k) + \sum_i c_p \rho \epsilon_{ik} d_{ik} \frac{(t_i - t_k)}{\delta_{ik}} \qquad (3).$$

The first term on the right hand side represents convection of energy in from the solid walls of the sub-channel. The last term is again a mixing term, analogous to the mixing term in equation (1).

(In differential form this term has the form

$$c_p \rho \epsilon \frac{(\text{differential area})}{dx} \frac{\partial t}{\partial y} \qquad (4).$$

where y indicates the direction normal to the differential area.)

II.C. OTHER DIFFUSION PROBLEMS:

Equation (1) describes the diffusion of momentum, while equation (3) describes the diffusion of thermal energy. Similar equations describe the diffusion of chemical species.

Experiments made to determine the rate of mixing, or the size of the mixing term, are usually made by injecting some chemical into the coolant stream and sampling the coolant stream at downstream stations.

Equations analogous to equation (3) then transform the chemical concentration data into mixing data, the primary quantity desired being ϵ_{ik}.

II.D. SOME CONCLUDING REMARKS:

It will be noted that the term $(\rho\epsilon_{ik})$ occurs in the mixing terms of both equations (1) and (3). It has the dimensions of a flow rate per unit of length, kg/sec m. For that reason, it is sometimes called an "interchannel flow rate" or a "mixing flow rate" or by some similar designation. But the term

$$\rho \epsilon_{ik} \frac{d_{ik}}{\delta_{ik}} \stackrel{\Delta}{=} w'_{ik} \qquad (5).$$

has the same units and so is also sometimes called by the same names. Therefore, when data are presented in terms of such flow rates, it is necessary to check carefully how the data have been reduced and which "flow rate" is actually meant.

Three additional considerations deserve passing notice at this point. First, the difference equations (1) and (3) characterize the momentum and energy exchange at an interface by just two regions: the sub-channel from whence the fluid immediately comes, and the adjacent sub-channel to which it is immediately going. Thus the equation claims that the fluid remains long enough in a given sub-channel to take on the characteristics of that sub-channel completely, and to "forget" all the characteristics of other channels through which it has previously passed. In other words, the formulation emphasizes the diffusional aspect of the transport and neglects any gross convective effects, for which cases the transport would not be proportional to the velocity or temperature gradient. Some of the mixing data available in the literature show clearly that under some circumstances this assumption is entirely unjustified. This aspect will be discussed again in the following sections.

The second consideration concerns the difference between the eddy diffusivity for momentum, to be used in the momentum equation, and the eddy diffusivity for thermal energy, which is used in the energy equation, and the eddy diffusivity for chemical species, the quantity determined by most experiments. Strictly speaking, although these quantities are closely related, they are not equal. Nevertheless, in most situations they do not differ by very much. In any case, the inaccuracies involved in predicting mixing are so great that it is not worthwhile to worry about any small differences in this respect.

Third, equations (1) and (3) imply no restrictions on the mixing flow rates w'_{ik}. For fully developed flow, however, the condition of conservation of mass requires for each sub-channel i that

$$\text{total mixing flow out of } i = \text{total mixing flow into } i \quad ,$$

which is to say

$$\sum_k w'_{ik} = \sum_k w'_{ki} \tag{6}$$

for all sub-channels k bordering on i. For all the data reported here, however, the various data reduction schemes have all employed the stronger general condition

$$w'_{ik} = w'_{ki} \quad , \tag{7}$$

that is, for each interface the mixing outflow equals the mixing interflow. This assumption may contribute errors in mixing data, particularly if cross flows are present.

These three considerations (among others) imply a certain amount of inaccuracy in the mixing data presented in the literature. However, most applications which require mixing data do not require very accurate data. Frequently adequate predictions of velocities and pressures in rod bundles can be made with only crude estimates of the eddy diffusivity. Sometimes only the right order of magnitude is required.

For these reasons one neither requires nor expects too much of the experimental data available.

III. MIXING AROUND BARE RODS:

III.A. DATA FROM THE LITERATURE:

References (2 - 6) present mixing data taken from bundles of rods without mixing promoters. The reports give the data in various forms according to the various purposes for which the data was taken. For comparison purposes Table 1 displays all this data reduced to the same form. The table presents the mixing data as

$$\frac{w'_{ik}}{w_i} \triangleq \frac{\rho \, \epsilon_{ik} \frac{d_{ik}}{\delta_{ik}}}{w_i} \quad . \qquad (8).$$

Equations (1) and (3) indicate the origins of this mixing term. The sub-channels denoted by the index i are shown in figure 1. The symbol w_i denotes the flow rate (mass time^{-1}) in a sub-channel. The factor w'_{ik} is actually defined by equation (8); it is intended to suggest the rate of mixing flow exchanged between adjacent sub-channels i and k through one common interface of width d_{ik} , per unit of length of flow. Thus w'_{ik} has the units (mass time^{-1} length^{-1}), and the mixing variable w'_{ik}/w_i has the units (length^{-1}).

In some reports the authors have omitted some information which is required to compute the Reynolds number or to reduce the data to the form w'_{ik}/w_i. In those cases the missing data have been assumed. These assumptions are indicated by question marks (?) in the table, and all computed data affected by the assumption are similarly marked.

Data neither given nor required are indicated by a horizontal dash in Table 1.

III.B. A PREDICTING METHOD:

A mere collection of mixing data from the literature would be mildly interesting but not of great usefulness. What is needed is some method for predicting the mixing so that predictions can be compared to the data and some insight gained into the problem.

Kattchee and Reynolds (1) suggest a method for predicting mixing around bare rods. The method equates the turbulence eddy diffusivity in the sub-channel, ϵ_i, to that in the center of a circular tube with a fluid flow at the same Reynolds number as in the sub-channel:

$$Re_i \triangleq \frac{4w_i}{\mu b_i} , \qquad (9).$$

where w_i is the flow rate in the i-th sub-channel, and b_i the wetted perimeter of the sub-channel. An empirical formula for the eddy diffusivity at the centerline of a circular pipe, given by (1) is

$$\frac{\epsilon}{\nu} = \frac{Re}{20}\sqrt{\frac{f}{2}} . \qquad (10).$$

Therefore we estimate ϵ_{ik} in equations (1), (3), and (8) with equation (10):

$$\frac{\epsilon_{ik}}{\nu} = \frac{\epsilon_i}{\nu} = \frac{Re_i}{20}\sqrt{\frac{f_i}{2}} \qquad (11).$$

where we find f_i using Re_i and empirical data for circular tubes.

Equations (8), (9), and (11), when combined, yield a prediction of the mixing w'_{ik}/w_i of the form

$$\frac{w'_{ik}}{w_i} = \frac{2\sqrt{2}}{20} \sqrt{f} \frac{d_{ik}}{\delta_{ik} b_i} \qquad (12).$$

which has been used to generate the predicted mixing rates shown in Table 1. These rates are thus the mixing rates expected from the general normal turbulence level in the flow along the rod bundle.

Kattchee and Reynolds (1) actually suggest the use of an average ϵ_{ik} , based on an ϵ_i computed for the i-th sub-channel and an ϵ_k computed for the k-th sub-channel, in order to allow for cases where the i-th and the k-th sub-channels are not identical. And in fact for most of the experiments reported here the adjacent sub-channels are not identical. However, the differences are small and in any case only a mean velocity over the entire rod bundle is available for computing the sub-channel flow rates. Therefore in the predictions made by equation (12) the rod lattice was taken as infinite, with all sub-channels identical.

III.C. COMPARISONS:

Table 1 shows the data and the predictions for mixing around bare rods. In particular, the last column shows the ratio of the measured mixing rate to the mixing rate predicted by equation (12) for the same geometry and Reynolds number as pertained to the test. The predictions range from a factor of 16 too low to a factor of 2 too high.

Furthermore, it is difficult to find a pattern in the discrepancies between data and predictions. The situation for the data of references (3, 4, 5), whose experimental situations were roughly similar, is very bad, the predictions for these data being wrong in a very unsystematic way, varying between factors of 9 and 1.5 too low.

The best pattern seems to appear in a plot of the ratio of observed to predicted mixing vs. the predicted mixing, shown in Figure 4. Despite the scatter in the center of the plot, there is a perceptible trend downward to the right. The greater the mixing is expected to be, then the greater should be the accuracy of the expectation.

III.D. CONCLUSIONS:

The agreement between data available in the literature and predictions made by the method of Kattchee and Reynolds (1), equation (9), is not very satisfactory. It is not clear, however, whether the discrepancies between data and predictions are due to a poor predicting method, or unreliable data, or both. Figure 4 indicates, however, that the data available should not be regarded as very accurate, a great amount of scatter being plainly evident.

It is likely that the data in many instances are unreliable, as many of the experimenters report that only slight variations in experimental conditions disturbed the mixing results appreciably. The effects of rod misalignment and cross-flows seemed to be especially large. In addition, one can suggest as a source of error extra turbulence introduced by the tracer fluid injection and pick-up system. In addition, it may have happened that some experimenters located their injection and pick-up apparatus far enough upstream in the rod bundle so that the velocity profile was still developing, with bad effects on the data.

Finally, none of the references attempt to estimate their overall experimental uncertainty. The reported mixing rates are, after all, computed quantities. The measured quantities in the mixing experiments are some kind of chemical concentration versus length. These are then converted into mixing rates by a lumped parameter model of the mixing process. It is quite possible that small uncertainties in the measured concentrations yield large uncertainties in the computed mixing rates.

It may also be that the predicting method is not too satisfactory. It could perhaps be improved by some attempt to take account of the lumping error, that is, the amount by which $(c_k - c_i)/\delta_{ik}$ departs from $\frac{\partial c}{\partial y}$, but there is some question whether this would be desirable if the same is not done in reducing the raw data to obtain the experimental mixing rates.

There the matter must rest, without a clear result other than that it seems likely that the data available are not reliable.

IV. MIXING AROUND RODS WITH FINS OR WIRE WRAPS:

IV.A. DATA FROM THE LITERATURE:

References (2, 3, 5), which presented data used in the previous section, also give mixing data taken from bundles of rods with fins and wire wraps. In addition, references (13 - 16) provide data only from bundles with wire wraps.

These data, presented in the reports in various forms, has been reorganized in the manner described in Section III for data from bare rods. Table 2 presents the reorganized mixing data, along with the relevant geometry and flow specifications for each experiment.

IV.B. PREDICTING METHODS FROM THE LITERATURE:

1. Method of Kattchee and Reynolds (1).

As in the previous section, a simple tabulation of the available data is not very useful. Again it is necessary to compare the data to predictions in order to gain insight into the problem.

One obvious choice of a predicting method is the method proposed by Kattchee and Reynolds (1) for bundles of bare rods, as used in the previous section. It is true that the method did not seem to work out so well in that case, but the fault was probably due more to the data than to the predicting method. In any case, predictions by this method have been made for each data point for mixing with fins or wraps, and these predictions are also tabulated in Table 2.

2. Method of Collins and France (2).

Collins and France (2) suggest that w'_{ik}/w_i should be equal to the ratio of the cross sectional flow area swept by the fins to the total cross flow area, divided by the flow length:

$$\frac{w'_{ik}}{w_i} = \frac{1}{L}\,\frac{A_{fi}}{A_i} \qquad (13).$$

This suggestion is patently absurd since for fully established flow the mixing w'_{ik}/w_i cannot be a function of the flow length. In addition, the pitch of the fins, omitted from equation (13), obviously will have an important effect on the magnitude of w'_{ik}/w_i .

3. Method of Shimazaki and Freede (13) and Waters (5).

Both Shimazaki and Freede (13) and Waters (5) suggest that the product of the mixing w'_{ik}/w_i and the fin or wrap pitch p should be a constant for a given rod geometry (rod diameter and rod pitch). This is equivalent to saying that each revolution of fin or wrap carries a definite fraction of the total flow with it, no matter what the pitch is.

Shimazaki and Freede (13) reported only one data point, and so were unable to evaluate their suggestion in detail, but the later work of Waters (5) embraces a series of experiments on one rod bundle but with various rod pitches. Waters shows that for his bundle the quantity $w'_{ik}p/w_i$ is indeed almost constant over a wide range of wrap pitch.

The quantity $w'_{ik}p/w_i$ can hardly be a constant for all mixing situations however. Firstly, this mixing quantity depends upon the sub-channel shape chosen for analysis. Secondly, as Waters (5) points out, the rod bundle geometry must have some influence, especially the height of the fins compared to the diameter of the rods. Thirdly, we have no special reason to expect that the same fraction of the total flow will follow the fins for all Reynolds numbers. Very viscous fluids, for instance, should show much different mixing characteristics than fluids of low viscosity.

These objections notwithstanding, the Shimazaki-Freede-Waters suggestion remains of interest, and will be discussed again in a following section.

IV.C. A NEW SUGGESTED PREDICTION:

1. Predicted mixing rates.

Oddly enough, none of the references discussed above attempt to begin at the beginning and predict mixing rates in the simplest way possible, even though they all hint at such a prediction.

A simple prediction requires only a simple model of the mixing process. The following idealized mixing model will yield a useful prediction of the mixing rate:

In the model, the mixing comprises two parts: outward mixing away from the rods and fins into the centers of the sub-channels, and "lateral" or "peripheral" mixing around the rods from sub-channel to sub-channel. In harmony with the lumped parameter idea, the first kind of mixing (due to general disorderly turbulence) is, in the model, infinitely large and makes the velocity and temperature in a given sub-channel uniform.

The lateral mixing in the model on the other hand, derives entirely from the orderly action of the fins, which sweep along all the fluid in front of them from sub-channel to sub-channel as the main flow proceeds along in the direction of the axis of the rod bundle.

Thus Figure 2 shows schematically the basic computational picture. Consideration, for the moment, of the action of only one wire or fin will give a picture of the "basic mixing action", so to speak. What flow rate from sub-channel i to sub-channel k does this picture imply?

For this model, the mixing rate predicted is, in words,

$$\frac{\text{flow rate pushed by the wire from } i \text{ to } k \text{ per unit axial length}}{\text{total flow rate in sub-channel } i} = \frac{\text{fraction of the cross sectional area of } i \text{ which is swept by the wire}}{\text{axial distance required for the helically wrapped wire to pass through the sub-channel cross section}},$$

or, in symbols,

$$\left(\frac{w'_{ik}}{w_i}\right)_{\substack{\text{one}\\\text{wire}}} = \frac{(A_{fi}/A_i)}{(\theta p/2\pi)} \qquad (14).$$

As equation (14) may not be self-evident, the Appendix gives a derivation.

This result for the basic mixing action, although it must in some way be related to the actual mixing, cannot really predict even the idealized mixing.

In the first place, the model only shows fluid leaving sub-channel i, whereas the true mixing idea pictures an equal rate of inflow through the interface from sub-channel i. Secondly, in most geometries two wires, each on adjacent rods, are attempting to sweep fluid through the same interface. Each, therefore, cannot be perfectly effective.

How then does the basic mixing calculated for one wire, equation (14), relate to w'_{ik}/w_i ?

Presumably the mixing situation is too complicated to allow a simple pencil-and paper answer to this question. Therefore, at this point the "analysis" ends, and the mixing study starts the following program:

1. Assume that equation (14) gives the mixing w'_{ik}/w_i, and make mixing predictions on this basis for experimental geometries reported in the literature.

2. Compare these predictions to the mixing data reported in the literature.

3. Seek a pattern in the discrepancies between prediction and experiment; try to find parameters which correlate the errors.

The antepenultimate column of Table 2 shows the predicted mixing rates which result from steps (1) and (2) above. A comparison, summarized in the penultimate column, of this column with the experimental mixing rates shown in the first of the mixing rate columns, shows the discrepancies between the simple mixing predictions and the data.

Section 2. below describes the third and final step in the program.

2. Correlation of discrepancies between data and predictions.

a. "Slipping over the fins"

A correlation of the errors requires at least a modest analysis of the sources of error. Undoubtedly part of the error comes from the "slipping" of some of the fluid over the fins; contrary to the fin sweeping assumption above, the fins cannot sweep all the fluid in front of them.

Simple physical reasoning can reveal a useful correlating variable for this source of error. Briefly, "slipping" should increase with increases in

1. The "axial inertia" of the flow, describing the tendency of the flow to persist in the axial direction,

2. the "obliqueness" of the fins across the axial direction of flow, equal to D/p,

3. the peripheral spacing between fins or wires on a rod;

and "slipping" should decrease with increases in:

1. the "viscous forces" in the flow,

2. the height of the fins.

A simple combination of these has the form

$$\text{"slipping"} \propto \frac{(\text{"axial inertia"})(D/p)(\sigma)}{(\text{"viscous forces"})(h)}$$

which gives directly the desired correlating variable

$$\text{"slipping"} \propto \frac{Re}{(\frac{p}{D})\ (\frac{h}{\sigma})} \qquad (15).$$

Denote this proposed correlating variable by CV. Then, if the error is evaluated in terms of

$$R \quad \triangleq \quad \frac{\text{predicted mixing}}{\text{observed mixing}}$$

then R should increase with CV. As CV increases, the slipping over the fins increases and the simple prediction of mixing, based on perfect fin sweeping, should more and more exceed the actual mixing.

b. Other geometrical effects.

The situation at the interfaces should contribute other important errors, especially if two fins or wires try to push fluid through the same space at the same time. The errors should depend on whether the wires or fins are turning in the same direction through the interface ("confluent") or in oposite directions ("opposing").

It seems that simple physical reasoning cannot provide even a semi-quantitative picture of these effects. Hopefully, however, a plot of the errors versus the correlating variable CV will reveal something about these effects by showing different error trends for the different geometrical arrangements, as illustrated qualitatively by Figure 3.

IV.D. COMPARISON AND DISCUSSION:

The data are tabulated in Table 2, but it is easier to see the results in graphical form. Figure 5 shows the ratio R of the mixing rate predicted by equation (14) to the measured mixing reported by various experimenters, plotted versus the proposed correlating variable, CV.

The data fall into a surprisingly orderly pattern, considering the inherent inaccuracies in the mixing experiments. As expected, R increases with increases in the correlating variable CV. Also as expected, the data tend to cluster into groups according to the arrangement of the mixing promoters. The relation between the data of references (3) and (16) is very nice in this respect. The data of Waters (5) lie perhaps a little higher than might be expected, but this is probably due to the rather conservative manner of data reduction to which Waters (5) explicitly refers.

The data of Waters (5) display a "wrong" trend at lower values of CV, but this again may stem from overconservative data reduction in these cases. In any case, the "wrongness" of the trend is well within a ± 25% interval, and presumably most mixing experiments show this much uncertainty.

Reference (14) provides the only data for a square lattice, and thus little may be concluded here.

Reference (2) provides the only data for mixing with fins rather than wire wraps. As might be expected, the mixing seems greater in this case than for wire wraps.

Figure 6 shows what is essentially the same mixing data as is shown in Figure 5, but this time organized according to the suggestion of Waters (5) and Shimazaki and Freede (13) discussed in Section IV.B.3 above. The ordinates are the dimensionless mixing quantities $w'_{ik}p/w_i$. The abscissæ are the proposed correlating variable CV discussed in Section IV.C.2 and used in Figure 5.

Thus Figure 6 is the same as Figure 5 except that the geometry factor A_{fi}/A_i is missing from the ordinates. One would therefore expect the correlations to be worse than in Figure 5, but in fact the patterns displayed are almost as satisfactory because for the experiments reported the range of A_{fi}/A_i was not so large, lying between about 0.42 and 0.59.

IV.E. CONCLUSIONS:

All considered, the pattern that the data present in Figure 5 is both orderly and plausible, and the plot should provide a good basis for estimating mixing rates for rod bundles with mixing promoters. The uncertainty is perhaps ± 50% even for the best known cases, but it usually is not necessary to know the mixing rate to a greater accuracy.

The patterns shown in Figure 6 are also good. This plot offers a more restricted basis for data correlation, however, as the ratio A_{fi}/A_i, expected to be important, is not included.

V. DISCUSSION AND OVERALL CONCLUSIONS:

It is evident that the simple diffusive picture of mixing used by the various experimenters in reducing their data, and also used in this report as the basis of mixing predictions, may suffer from errors from numerous sources. It is entirely likely that some of these errors are truly major ones that therefore one can expect neither much consistency among the data nor good agreement between data and predictions.

A consideration of the possible sources of major error should take into account that:

1. The basic diffusion assumption that the mixing rate of any quantity is proportional to the gradient in concentration does not always describe what happens in mixing. For mixing with fins or wraps, the concentration versus flow length plots of (5) and (13) show that gross convection effects are considerable. Even in mixing without fins, the size of the turbulent eddies may be so large that the mixing process is not primarily diffusive in nature.

2. The mixing flow pattern may not obey the symmetry expression (7), in which case the data reductions of the various experimenters would have no real meaning.

3. Extra turbulence introduced by entrance effects, or by the measuring apparatus, may exceed the normal turbulence.

4. Lumping errors may be large, especially for S/D $\approx$ 1.

5. The mixing rate obtained by reduction of concentration data is rather sensitive to errors in the raw data.

Considering these sources of possible error, it is hardly surprising that the data for mixing around bare rods, summarized in Figure 4, seem rather inconsistent, the ratio of observed to predicted mixing scattering over almost a whole decade. Mixing in this case cannot be predicted to within a factor of 3. This may, however, be good enough, depending on the specific application in question.

It is ironic that the data for mixing with fins and wire wraps, which at first glance seem even more difficult to measure accurately or to predict, show a much neater and more understandable pattern than the data for mixing without mixing promoters. The available data make as good a pattern as could be expected, given the uncertainties in the experiments and the data reduction, and the pattern is good enough to make some fairly accurate mixing rate predictions possible. Over the range of the correlating variable considered, predictions may perhaps be as accurate as ± 50%.

As a final note, a recurring question concerns how much the mixing around the rods of a bundle is improved, over the bare rods case, when fins or wraps are added. Kattchee and Reynolds (1) suggest an increase by a factor from 2 to 5. The data comparison in the final column of Table 2 for those cases where experimenters have reported data both with and without fins shows that this suggestion is not far wrong for the systems studied. The mixing rate without fins, however, generally exceeds predictions made by the method of Kattchee and Reynolds (1). Therefore it seems better to predict mixing for wraps or fins in terms of Figure 5, rather than by using the Kattchee-Reynolds method to predict the mixing without fins and then multiplying by a factor of from 2 to 5.

ANNOTATED BIBLIOGRAPHY

GENERAL

Kattchee and Reynolds (1) provide an overall introduction to the computation of coolant velocity and temperature distributions by a finite difference technique and give discussions of many aspects of the problem:

1. Kattchee, N., and Reynolds, W.C.: "Hectic II - An IBM 7090 Fortran Computer Program for Heat Transfer Analysis of Gas or Liquid Cooled Reactor Passages,

   Aerojet-General Nucleonics, San Ramon, California, IDO - 28595, December, 1962.

MIXING WITHOUT PROMOTERS

The following references report the data for mixing around bare rods which are analyzed in Section III above:

2. Collins, R.D., and France, J.: "Mixing of Coolant in Channels Between Close-Packed Fuel Elements",

   United Kingdom Atomic Energy Authority, Research and Development Branch, Capenhurst, IGR - TN/CA - 847, January, 1958.

3. Bishop, A.A., et al.: "Thermal and Hydraulic Design of the CVTR Fuel Assemblies. Topical Report",

   Westinghouse Electric Corp., Atomic Power Division, Pittsburgh, Pennsylvania, CVNA - 115, June, 1962.

4. Nelson, P.A., et al.: "Mixing in Flow Parallel to Rod Bundles Having a Square Lattice",

Westinghouse Electric Corp., Atomic Power Dept., Pittsburgh, Pennsylvania, WCAP - 1607, July, 1960.

5. Waters, E.D.: "Fluid Mixing Experiments with a Wire-Wrapped 7-Rod Bundle Fuel Assembly",

General Electric Co., Hanford Atomic Products Operation, Richland, Washington, HW - 70178, August 3, 1961.

6. Bell, W.H., and Le Tourneau, B.W.: "Experimental Measurements of Mixing in Parallel Flow Rod Bundles",

Westinghouse Electric Corp., Bettis Plant, Pittsburgh, Pennsylvania, WAPD - TH - 381, 1958.

There are various reports available which can serve as supplements to the reports listed above. Bishop, et al., (7) is an abstract of work reported in more detail in (3). Reference (7) omits important information and has not been used as a data source. Waters (8) is a newer edition of (5), but contains no new data.

7. Bishop, A.A., et al.: "Coolant Mixing in a Nineteen-Rod Fuel Assembly",

Transactions of the American Nuclear Society, Vol. 4, 1961, pp. 43 - 44.

8. Waters, E.D.: "Fluid Mixing Experiments with a Wire-Wrapped 7-Rod Bundle Fuel Assembly",

General Electric Co., Hanford Atomic Products Operation, Richland, Washington, HW - 70178 REV, November, 1963.

References (9) and (10) are predecessors to reference (6). They contain no experimental data, but only discuss the mixing problem in general terms:

9. Bohl, H., et al.: "Mixing Coefficients",

Westinghouse Electric Corp., Atomic Power Dept., Pittburgh, Pennsylvania, WAPD - PM - 41, September, 1955.

10. Grimble, R.E., and Bell, W.H.: "An Analysis of Mixing in Parallel Flow Rod Bundles",

Westinghouse Electric Corp., Westinghouse Atomic Power Division, WAPD - TH - 178, 1956.

Reference (11) provides a literature survey of the mixing problem, made by Atomic Energy of Canada Limited. References listed in that report and which contain data and which have been released to the public have been included in the present report.

11. Coates, D.F.: "Inter-Channel Mixing and Cooling Temperature Distribution in Seven and Nineteen Element Fuel Bundles - Literature Survey",

Canadian General Electric Co., Ltd., Peterborough, Ontario, Canada, AECL - X07 - 10001 R, November, 1960.

It is possible that an interesting predicting method is reported by Zaloudek (12); however, this report was classified for some time. It has now been declassified but withdrawn from circulation while the author is preparing the work for publication.

12. Zaloudek, F.R.: "An Analysis of the Magnitude of Natural Mixing in the Seven Rod Cluster Fuel Assembly without Mixing Promoters",

General Electric Co., Hanford Atomic Products Operation, Richland, Washington, HW - 60376, May 20, 1959. (Classified).

MIXING WITH PROMOTERS

Mixing data for rod bundles with fins and wire wraps are given in references (2, 3, 5), previously cited. Shimazaki and Freede (13) and McNown, *et al.* (14) provide additional data.

13. Shimazaki, T.T., and Freede, W.J.: "Heat Transfer and Hydraulic Characteristics of the SRE Fuel Element",

Reactor Heat Transfer Conference of 1956,

J.E. Viscardi, Comp., TID - 7529, Part 1, Book 1, U.S. Atomic Energy Commission, 1957.

14. McNown, J.S., *et al.*: "Tests on Models of Nuclear Reactor Elements. II. Studies on Diffusion",

Engineering Research Institute, University of Michigan, Ann Arbor, Michigan, AECU - 3757 (Pt. II), March, 1957.

Two reports (15, 16) stemming from Canadian work provide valuable additional mixing information. Unfortunately, neither is complete, reference (15) being a brief journal survey article, and reference (16) being a rather terse internal report. Between the two, however, some useful data may be extracted.

15. Lane, A.D., et al.: "The Thermal and Hydraulic Characteristics of Power Reactor Fuel Bundle Designs",

    The Canadian Journal of Chemical Engineering, Vol. 41, No. 5, October, 1963, pp. 226 - 234.

16. Howieson, J., and McPherson, G.D.: "Coolant Mixing in 19Element Fuel Bundles",

    Atomic Energy of Canada Limited, Nuclear Power Plant Division, Toronto, Ontario, Canada, TDSI - 31, July, 1961.

Mensforth and Yonemitsu (17) describe some interesting mixing experiments on wire wrapped bundles, but the experiments yielded no quantitative results.

17. Mensforth, L.H., and Yonemitsu, I.D.: "Seven Element Fuel Bundle Flow Studies",

    Canadian General Electric Co., Ltd., Civilian Atomic Power Department, Peterborough, Ontario, Canada, R 60 CAP 25, June 15, 1960.

A P P E N D I X

DERIVATION OF FIN-SWEEP MIXING PREDICTION

Figure (2) shows the control volume for analysis, seen along the axial direction. The axial flow through this area is w_i, and the axial velocity V is assumed constant over the cross section, even in the area swept by the fins. (This should be a reasonable assumption if the fin pitch to rod diameter ratio is large, as it usually is.) Thus we have

$$w_i \stackrel{\Delta}{=} \rho A_i V_i \qquad \text{(A-1).}$$

The fin sweeping flow per unit of axial length, w'_{ik}, upon the assumption that the fins smoothly sweep forward all the fluid in front of them, is

$$w'_{ik} = \rho\omega \int_{r_i}^{r_o} r\, dr \qquad \text{(A-2).}$$

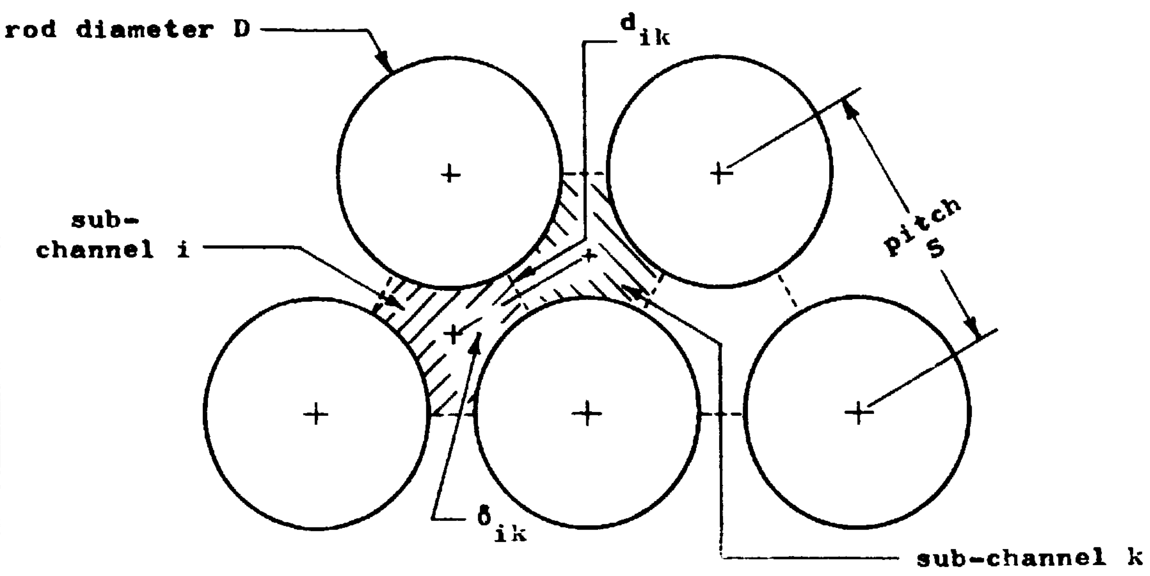
where ω is the "rotational velocity" of the fins through the cross section. We take

$$\omega = \frac{2\pi}{\begin{array}{c}\text{(time for a}\\ \text{full rotation)}\end{array}} \qquad \frac{2\pi}{(p/V_i)} \qquad \text{(A-3).}$$

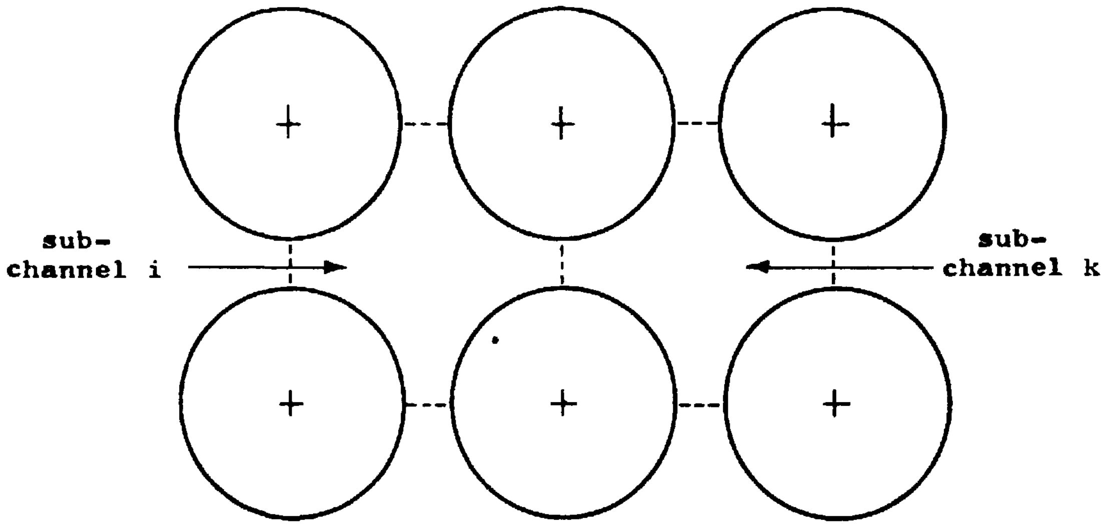
Combining equations (A-1), (A-2) and (A-3), we have

$$\frac{w'_{ik}}{w_i} \approx \frac{2\pi \int_{r_i}^{r_o} r\, dr}{pA_i} = \frac{\theta \int_{r_i}^{r_o} r\, dr}{(A_i\, \theta p/2\pi)} = \frac{(A_{fi}/A_i)}{(\theta p/2\pi\ )} \qquad \text{(A-4).}$$

where A_{fi} represents the area in the i-th sub-channel which is swept by the fins.



Triangular Lattice



Square Lattice

Figure 1.

SUB-CHANNEL DEFINITIONS

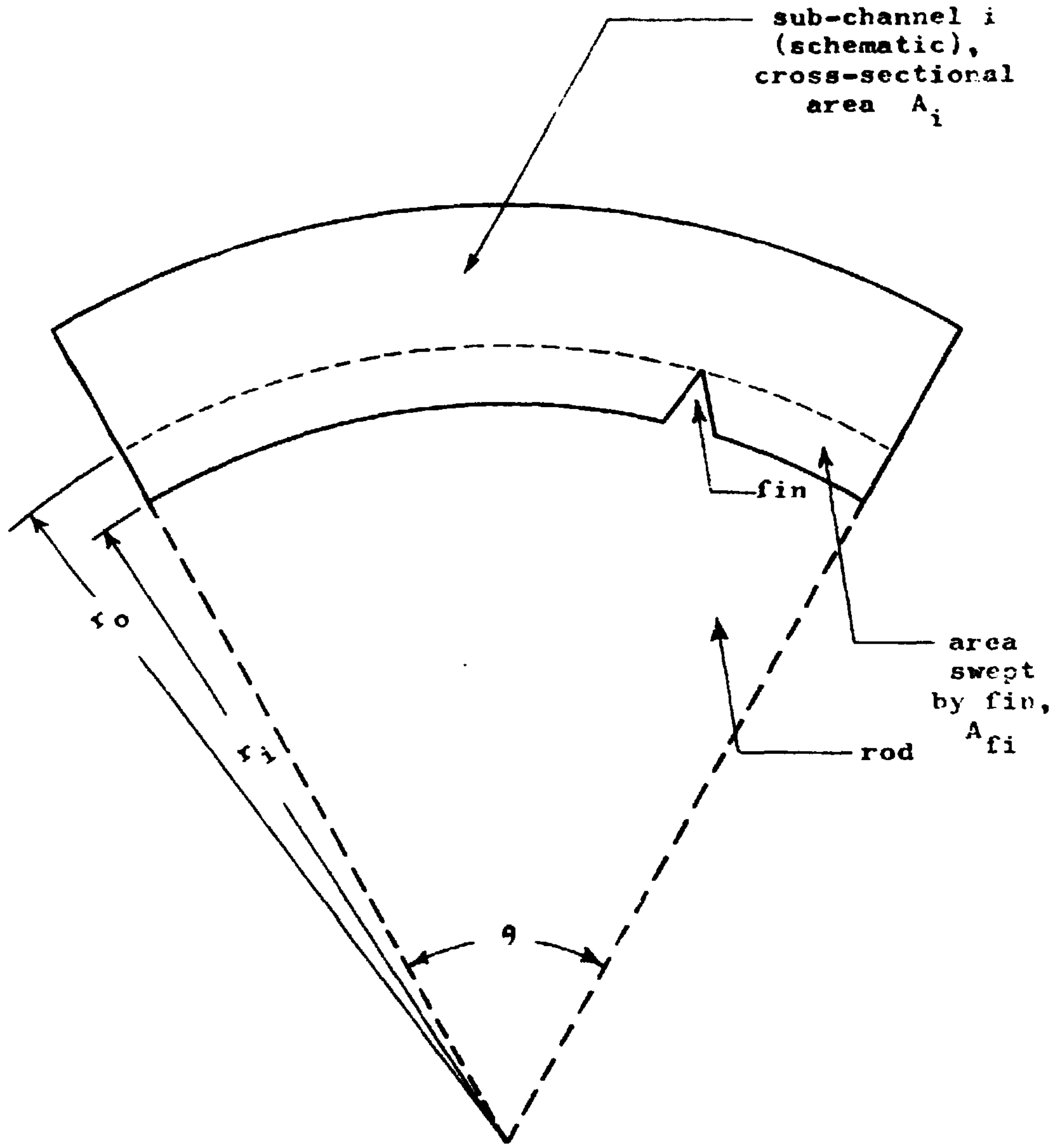


Figure 2.

SCHEMATIC DIAGRAM FOR FIN-SWEEP
MIXING RATE CALCULATION

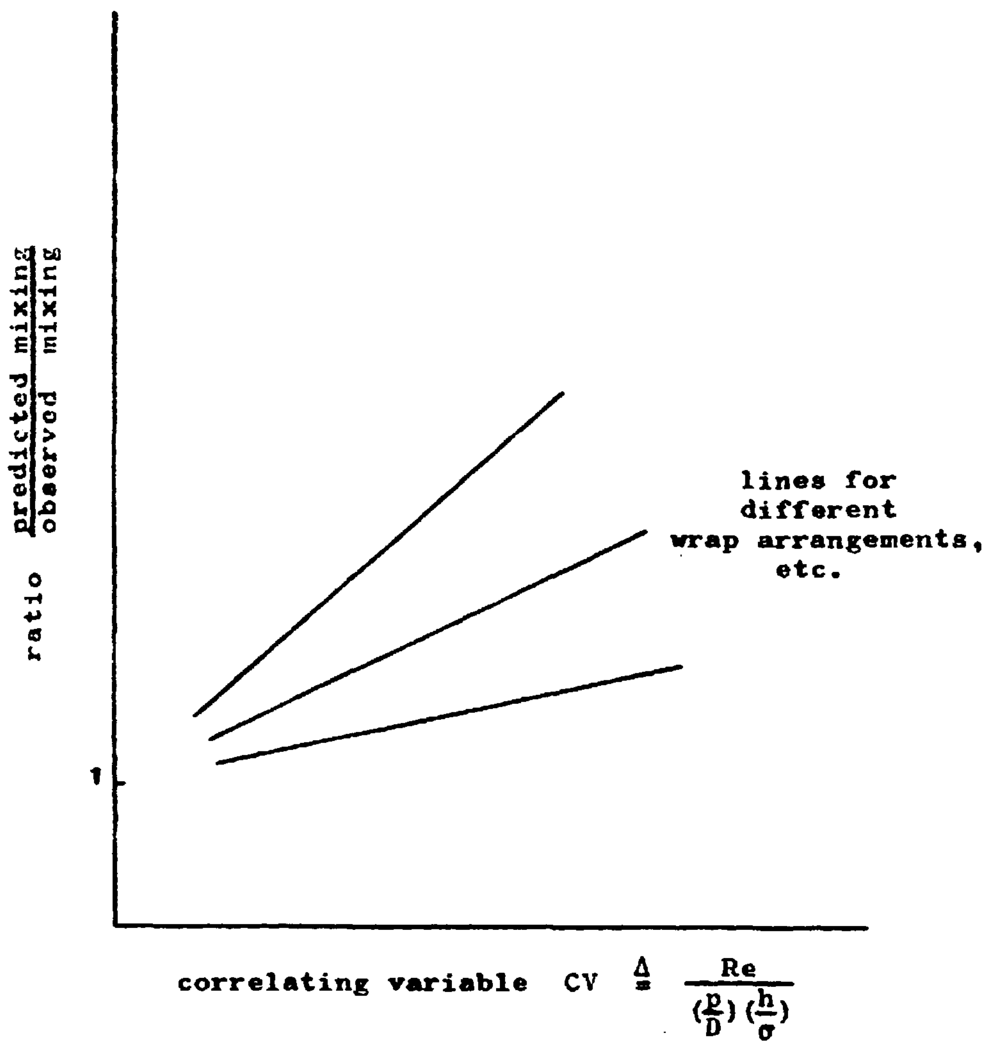


Figure 3.

QUALITATIVE PLOT OF EXPECTED TRENDS FOR RATIO OF PREDICTED TO OBSERVED MIXING AS A FUNCTION OF THE CORRELATING VARIABLE CV, WITH PIN OR WIRE WRAP GEOMETRY AS PARAMETER

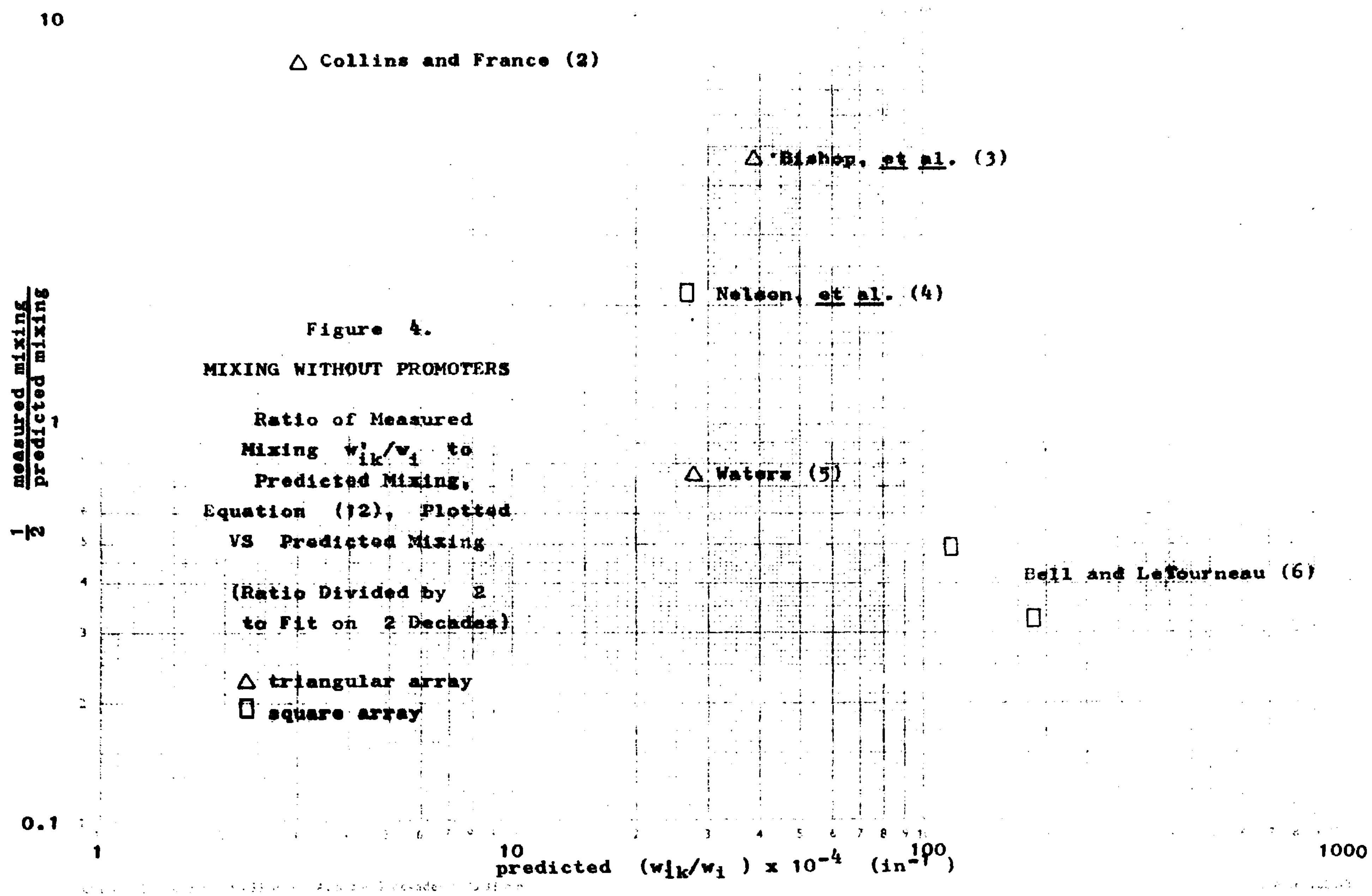


Figure 4.

MIXING WITHOUT PROMOTERS

Ratio of Measured Mixing w'_{ik}/w_i to Predicted Mixing, Equation (12), Plotted VS Predicted Mixing

(Ratio Divided by 2 to Fit on 2 Decades)

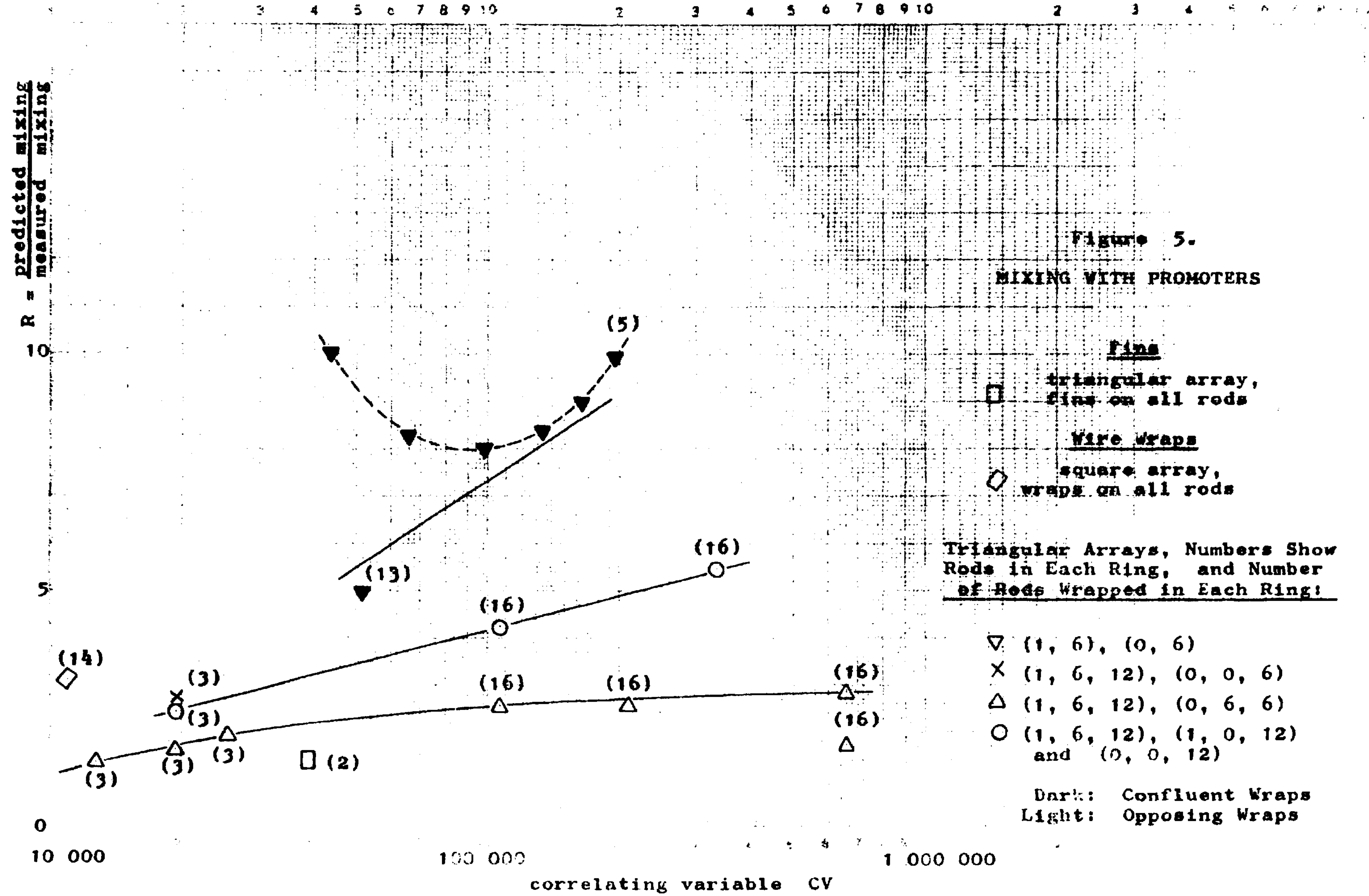


Figure 5.

MIXING WITH PROMOTERS

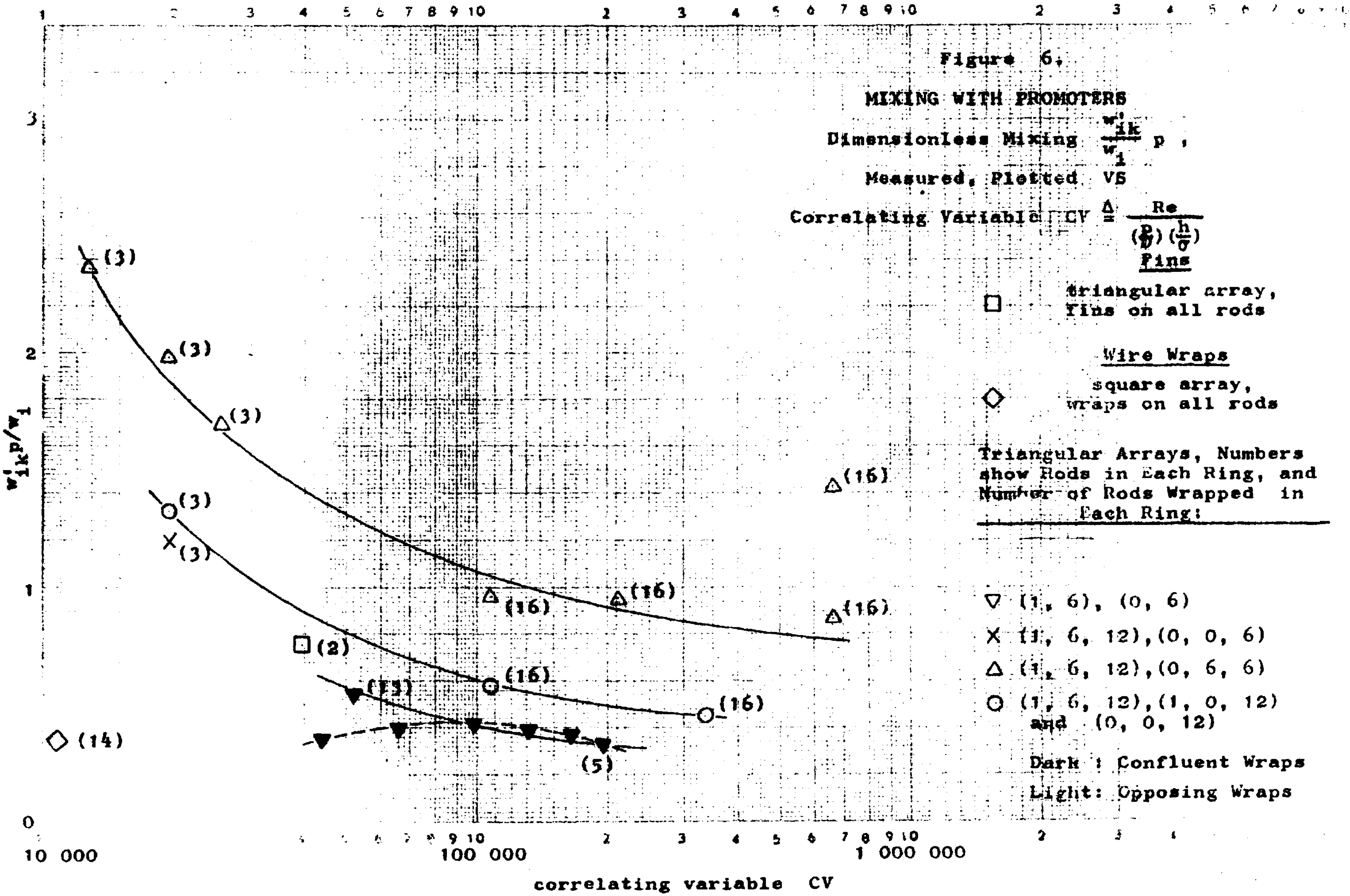


Figure 6.
MIXING WITH PROMOTERS
Dimensionless Mixing $\frac{w'_{ik}}{w_i}$ p ,
Measured, Plotted VS
Correlating Variable CV $\triangleq \frac{Re}{(\frac{P}{D})(\frac{h}{D})}$
Fins
triangular array, fins on all rods
Wire Wraps
square array, wraps on all rods
Triangular Arrays, Numbers show Rods in Each Ring, and Number of Rods Wrapped in Each Ring:
(1, 6), (0, 6)
(1, 6, 12), (0, 0, 6)
(1, 6, 12), (0, 6, 6)
(1, 6, 12), (1, 0, 12) and (0, 0, 12)
Dark : Confluent Wraps
Light: Opposing Wraps
$w'_{ik}p/w_i$
correlating variable CV
10 000
100 000
1 000 000

TABLE 1

DATA FOR MIXING AROUND BARE RODS

	GEOMETRY				FLOW				MIXING RESULTS		
Reference	No. and Array	Rod Dia. D (in)	Pitch S (in)	$\frac{S}{D}$	Fluid	Temp.	Velocity (ft/sec)	Re	Observed w'_{ik}/w_i $\times 10^4$	Predicted w'_{ik}/w_i $\times 10^4$	Ratio: $\frac{\text{Observed}}{\text{Predicted}}$
Collins and France (2)	19 Δ	3.50	3.875	1.10	Air at 1 at. (?)	Room (?)	≈ 100	58000 (?)	50 (in^{-1}) (?)	3.04 (in^{-1})	16.4
Bishop, *et al.* (3)	19 Δ	0.500	0.600	1.20	Water	-	-	37000	359	38.6	9.30
Nelson (4)	144 sq	0.337	0.422	1.25	Water	Room (?)	11.6	30000 (?)	113	26.6	4.25
Waters (5)	7 Δ	0.704	0.842	1.196	Water	-	-	75000	41.6	27.6	1.50
Bell and Le Tourneau (6)	64 sq	0.333	0.375	1.13	Water	-	-	10000 - 50000	115	117	0.98
		0.312	0.375	1.20	Water	-	-	10000 - 50000	122	187	0.65

TABLE 1

DATA FOR MIXING AROUND BARE RODS

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Waters (5)	7 Δ	0.704	0.842	1.196	Water	-	-	75000	41.6	27.6	1.50
Bell and Le Tourneau (6)		0.333	0.375	1.13	Water	-	-	10000 - 50000	115	117	0.98
	64 sq	0.312	0.375	1.20	Water	-	-	10000 - 50000	122	187	0.65

TABLE 2

DATA FOR MIXING WITH MIXING PROMOTERS

REFERENCE	ROD GEOMETRY			MIXING PROMOTERS				FLOW					MIXING RATES $w'_{ik}/w_i \times 10^4$ (in^{-1})				RATIOS	
	No. and Form	Rod Dia D (in.)	Pitch s (in.)	Description	No. per Rod, n	Height, h (in.)	Pitch p (in.)	Fluid	Temp	Velocity (ft/sec)	Re $\times 10^{-3}$	CV $\times 10^{-3}$	Observed With Fins	Observed Without Fins	Predicted by Eqn.(12)	Predicted by Eqn.(14), Fin Sweep Pred.	$\frac{\text{Sweep Pred.}}{\text{Obsd. With Fins}}$ $\hat{=}$ R	$\frac{\text{Obsd.With Fins}}{\text{Obsd.Without Fins}}$
Collins and France (2)	196	0.50	0.875	fins, opposing	6	0.156	57.8	air, at 1 at.(?)	room (?)	≈100	58 (?)	39 (?)	131	50	3.04	186	1.42	2.61
Shimazaki and Freede (13)	[illegible]	0.790	0.881	wire wrap, confluent, on outer rods	1	0.091	10.0	water	—	—	24	52	550	—	16	2730	4.96	—
Lane (15); Hewieson and McPherson (16)	19[illegible]	0.600	0.650	wire wrap, opposing, on center and 12 outer rods	1	0.050	18	water	—	25.5	85	107	322	—	13.6	1370	4.25	—
		1.88	2.03	ditto	1	0.166	56.1	water	—	25.5	265	18[illegible]	80.2	—	4.05	439	5.49	—
		0.600	0.650	wire wrap, opposing, 6 middle rods and 6 alternate outer rods	1	0.050	18	water	—	25.5	85	107	531	—	13.6	1370	2.59	—
		0.600	0.650	ditto	1	0.050	9.2	water	—	25.5	85	210	1040	—	13.6	2690	2.59	—
		[illegible]	[illegible]	ditto	1	[illegible]	9.2	water	—	25.5	265	658	1560	—	12.6	2690	1.72	—
		1.88	2.03	ditto	1	0.1[illegible]	[illegible]	water	—	25.5	265	658	302	—	4.05	860	2.85	—
McKeown, *et al.*, (14)	25sq	0.434	0.474	wire wrap, opposing (?), on all rods	1	0.040	9.[illegible]	water	70°F (?)	4	6.4 (?)	10.[illegible] (?)	394	—	8.15	1220	3.10	—
Bishop, *et al.* (3)	196	0.500	0.600	wire wrap, opposing, alternate outer rods	1	0.100	15.0	water	—	—	37	19.[illegible]	798	359	38.6	2170	2.74	2.22
				wire wrap, opposing, 6 middle rods and 6 alternate outer rods	1	0.100	15.0	water	—	—	24.4 37 48.[illegible]	12.3 19.4 25.5	1570 1320 1130	359	38.6	2170	1.38 1.64 1.92	4.38 3.69 3.16
				wire wrap, opposing, on center and 12 outer rods	1	0.100	15.0	water	—	—	37	19.4	880	359	38.6	2170	2.46	2.45
Waters (5)	74	0.704	0.842	wire wrap, confluent, on outer rods	1	0.138	18 12 8.0 6.0 4.8 4.0	water	—	—	70	43.8 65.8 98.5 131 164 197	193 333 518 659 768 831	41.6	27.6	1930 2750 4120 5500 6890 8280	10.0 8.29 8.00 8.40 9.00 9.92	7.0 12.1 18.7 23.8 27.3 30.[illegible]